

ADVANCES IN 3-DIMENSIONAL BRAIDING

Cirrelia Thaxton, Rona Reid, and Aly El-Shiekh
Mars Mission Research Center
College of Textiles
North Carolina State University
Raleigh, NC

ABSTRACT

This paper encompasses an overview of the history of 3-D Braiding and an in-depth survey of the most recent, technological advances in machine design and implementation. Its purpose is to review the major efforts of university and industry research and development into the successful machining of this textile process.

INTRODUCTION

The technology of 3-D Braiding epitomizes the evolution of ancient art and custom into the science of engineering a new, innovative textile process. Unlike other textile techniques like weaving and knitting, 3-D Braiding involves the continuous intertwining of two or more yarn groups in a bias direction, and the structure formed possesses remarkable structural integrity, high damage tolerance, torsional stability and characteristic handling ease [16]*. As this technology expands from university research to industrial manufacturing and development, careful investigation into the design and automation of successful braiding machines is imperative. Furthermore, the future growth of this technology depends on the ability of investigators to improve upon and modify processing parameters while reducing any process limitations. Accordingly, this paper addresses current advances in the area of 3-D braiding machines, focusing on the three main design areas: machine bed configuration, carrier design, and beat-up mechanisms. These three components are instrumental to the overall feasibility of a design for a modern 3-D braiding apparatus.

* (References 1-24 are cited in the text)

HISTORY

The origin of 3-D braiding can be traced to knot-tying, which is one of the oldest technologies known to man [17]. Since the beginning of time, man has ritualistically twisted and plaited hair for convenience, adornment and customs. This decorative styling of the hair developed into the practice of intertwining grass and natural fibers to form ropes and ornate embellishments in artwork and clothing design. In the ancient Orient, skilled artisans crafted intricate braids called Kara Kumi for ornamental purposes [21]. During the 17th century, English sailors devised spool braiders that formed braids for practical rather than artistic use. The spool braider or sinnet made braids that served a useful purpose as durable ropes [21]. The formation of braids for scientific rather than artistic means underwent a slow evolution until the mid-twentieth century.

During the next phase of development of braiding as an advanced technology, the practice of braiding was no longer considered only a crafting art. In the 1940's, W. T. Harburger authored a paper on the engineering structure of braids [17]. His paper addressed geometric factors relating to the concept of braiding. In the next decade, D. Brunnschweiler discussed the configuration, geometry, and tensile properties of tubular braids [17]. In the 1960's a plethora of new concepts involving the mechanisms of the 3-D braiding process evolved. An informative book by W. A. Douglas dealing with braiding machinery and processing parameters became a cornerstone for the growing technology [17]. Comprehensive patents by Bluck and General Electric established 3-D braiding as a technical process in the field of science and engineering. Emerging from this period of growth and innovation were two fundamental classifications for the braiding process, four-step and two step. Both classifications share two distinct machine types, regular and circular [13]. The former produced braids having right-angled corners, whereas the latter produced round cross-sectional shaped braids. In 1965, General Electric Reentry Systems Divisions invented the Omniweave braiding process for the production of multidirectional braids for aerospace composites. The 4-step machine incorporated sequential, discrete carrier motion as opposed to continuous motion [17]. GE claimed that the Omniweave would vary fiber orientation while braiding stiff, brittle fibers without delamination failure [13]. In 1969 the Bluck patent on "High-Speed Bias Weaving" detailed a

circular 4-step braiding machine for the production of hollow braids [13]. On the machine spools sitting beneath the braiding plane supplied yarns. During the process, these yarns moved through a network of holes in a guide nest which circumrotated the machine. This process was faster than its predecessors; however, entanglement of feeding yarns due to guide nest movement was a major limitation [13]. Consequently, the braided product had a fixed length and yarn delivery was intermittent.

In 1973 Maistre patented the first automated 3-D braiding machine. He promoted the new braiding process as SCODID, an acronym for Structure Composite Unidirectionelle Indelaminable (undelaminable, unidirectional composite structure) [13]. A regular-type, 4-step braiding machine, the SCODID had the capability to braid over 3200 yarns in simultaneous fashion. The yarn supply rose vertically and did not traverse the cross-section of the braid. The braided products had fixed lengths and two layers of yarn with adjoining edges [13].

In 1982, Florentine developed a versatile braiding machine for the production of complex-shaped 3-D preforms having integrated structural geometry and varying lengths. The Magnaweave, his 4-step regular braiding machine had a system comprised of 4 x 2 motion due to row/column shifts actuated by pneumatic cylinders, and manufactured braids possessing "SCODID" texture geometry [13]. Also, a combing or compacting movement followed an orthogonal shedding mechanism providing a high degree of freedom in material orientation control [9]. The Magnaweave had a counterpart, the Magnaswirl. This counterpart was a circular braider producing braids with circular cross-sections by three distinct motions: (1) ring or angular, (2) spoke or radial and (3) vertical or combing [16]. The design of the machine consisted of radial rows where carriers sat and a base track for tangential motion of arcuate members. The partial occupancy of the radially positioned rows by carriers produced tight braided structures [13].

Contributing further to the evolution of the 3-D braiding process was the invention of Through - the - Thicknesstm technology by Atlantic Research Corporation (ARC), which is considered in industry to be the leading authority on 3-D or Through - the - Thickness Braiding. The circular braider manufactured had concentric grooved rings and carriers capable of alternate row and column position shifts. During the process of Through - the - Thicknesstm braiding, a technique for manufacturing 3-D seamless patterns by continuous intertwining of fibers, the carriers situated on

the machine bed moved simultaneously [6]. The process was a major advancement exhibiting a novel textile technology of arranging fibers in irregular geometries for arbitrary thickness [8]. The braided products of this process had varying lengths, composite material toughness, and adequate delamination resistance.

As the present decade approaches the 22nd century, the advance of 3-D Braiding is inevitable. The current trend is toward computer-aided design and manufacture of the braiding process. Ko and his associates devised a computer simulation of the 4-step 3-D braiding procedure [17]. This system screened braid geometries for their respective cross-sections. Then, Brown and Harman used computer aided design to simulate the operation of a braiding machine and to trace the resulting yarn paths of the braid [18]. Developing areas of machine design and exploring multidirectional braiding techniques for near-net shapes of preforms through the extensive use of CAD/CAM technology are the future of composite engineering.

MACHINE BED DESIGN

The machine bed, a major component of any 3-D braiding apparatus, supports the precise movement of fiber-carrying devices (carriers or braiders). Accordingly, the purpose of the machine bed is to facilitate and expedite carrier placement along predetermined paths within the braiding plane. In recent years many configurations for machine beds of regular, circular, and variations of both types have been designed and tested.

The 3-D braiding group at North Carolina State University's (NCSU) College of Textiles designed and constructed a 2-step regular braiding machine. Its machine bed warrants attention due to its potential as a marketable advance. Consisting of an assembly of unit tiles made of aluminum plates embedded with orthogonal T-grooves, the 2-step braider utilizes a dual arrangement (Figure 1) [18]. The first prototype exhibited machine arrangement one, having machine sides parallel and perpendicular to slots. The prototype consisted of four (4) tiles. Each unit tile has dimensions of 12" x 12" x 1" and a distance of 3" between grooves (Figure 2) [19]. Each tile has a hole for axial insertion from spools underneath the braiding plane. Next, for the second arrangement, which reduces machine space, machine sides are parallel and perpendicular to the preform sides, being at 45° angles to the slots.

The actuation system embodies an array of stiffened timing gear-belts that push the carriers. While inside the machine bed grooves, the belt behaves like a "rigid rod" [18]. The flexible joint action occurs once the belt emerges from the groove and drops under its own weight. Also, the driving system utilizes stepping motors [20]. Four of the eight stepping motors drive the timing gears to control carrier stroke. The other four motors transport the driving units carriages across the perimeter of the machine bed.

The 2-step regular machine incorporates a computer terminal and controller as its control system. Utilizing a special motor control language, the braiding programs are written. The programs are transmitted to the CPU of the controller, while the APPCOR IMC-8 controller guides the action of the eight stepping motors (Figures 3 & 4) [19].

This prototype has many advantages. First, it can be easily manufactured and expanded as a result of its tile assembly construction of the machine bed. Second, the machine cost can be reduced because only eight stepping motors are needed regardless of machine size. Lastly, the mechanism of a horizontal rod driven by two air cylinders over the machine bed acts as a convergence device which eliminates the "over jamming" effect [18].

An emerging technology is in the area of multi-ply braiding. This concept involves the formation of braid with more than 2 layers (plies). Brown and Ratliff of ARC invented a technique to move the machine bed that was comprised of a sequenced braider motion for the multi-ply technology [7]. Patented in 1986, this method includes a machine bed configuration of a row/column carrier arrangement. When an intermediate row moves to block the motion of a column, a tamping force causes the column to shift to one side of the selected row [7]. This sequence of action makes carrier alignment in columns simpler.

This braiding innovation claims the following advantages: (1) machine jams are eliminated, (2) unjammed operation of a multi-ply braiding system is achievable and (3) lower cost, low tolerance multi-ply braiders may be used [7].

For circular braiders, row movement is caused by the shift of concentric rings. Column (radial) movement occurs when discrete carriers are shifted. A difficulty in machining of circular braiders arises due to the expense of producing properly fitting concentric rings [15]. Often, a circular braider is quite large, requiring ample space. Also jamming can occur when a large number of carriers shift radially.

Consequently an easily expandable 2-step braiding machine in circular form having no concentric rings was next designed and built by El-Shiekh and his colleagues at NCSU. The machine bed has 12 tiles arranged together to form a circular configuration (Figures 5 and 6) [13]. Each tile, made of aluminum, consists of axial tubes, magnets, stoppers, and braiding carriers. The yarn supply for the axials passes from a point above the plane of braiding down through the axial tubes where they are suspended by weights. The spooled carriers maintain a supply of up to fifteen feet of yarn.

On the machine bed a magnet attracts the carriers against yarn tensions. The action of the stoppers halts carrier movement maintaining adequate yarn tension. The bed has 48 slots in clockwise direction. Every slot is formed in the shape of an inverted "T" shape, which facilitates the in and out movement of the carriers [13]. Elimination of the jamming effect is a major advantage of this assembly. The carrier arrangement determines the required preform shape.

An ARC circular braiding machine was patented in 1988 by Richard Brown. The apparatus bed consists of a plurality of interchangeable rings having the same diameter (Figure 7) [4]. The rings are situated side by side in an axial arrangement. These ring members hold carriers that move axially and rotate about the central axis of the machine. During the braiding process, the Brown apparatus intertwines yarn by shifting adjacent carrier rows in opposing directions while spinning adjacent ring members in opposite directions. Notably, an actuating mechanism causes the ring rotation and propels the carrier rows in axial fashion to form the braid. This mechanism comprises a "manually or power driven actuator" that is connected to the rings through gears [4]. The actuation system for the carriers is composed of "slidable" rods or pistons which are situated at opposite carrier-row ends. These pistons may be driven pneumatically or mechanically.

The cylindrically designed circular braiding machine is a noteworthy advancement due to the following distinctions [4]:

- (1) ring members have same dimensions for ease in constructing the machine bed
- (2) ring members are both expandable and interchangeable
- (3) the machine requires little space and
- (4) the machine can produce axi-symmetric and cartesian braids.

ARC also patented a continuous circular braider comprised of a multitude of "flexible annular" members or belts. These belts support the carriers and are arranged in side by side fashion, axially

aligned [10]. The belts glide circumferentially relative to a central axis. The carriers, mounted on the belts move as well. An actuation device drives the belts and carrier rows along axial routes intertwining the fiber into a braided structure [10]. During the braiding process, the motion of adjacent carrier rows in opposing axial directions and the movement of adjacent belts in opposite circumferential directions initiate braid formation.

On this apparatus the mechanism of actuation consists of sensors mounted on the belts which activate engaging slots found on a sector-by-sector basis. After belt shifting occurs this actuating mechanism allows the sector positioning of sensors [10]. Next shoes, sliding mechanisms, are exchanged with belts in that one sector. This sequence of sensor positioning and shoe sliding repeats for each sector until the original sector is reached.

The Culp patent makes the following progressive claims [10]:

- (1) a multitude of belts are arranged axially to support carriers for axial motion,
- (2) the machine track supports and guides the belts along a circular path
- (3) a group of carrier rows are situated on the belts
- (4) an actuation device moves the belts circumferentially and carrier rows axially.

In 1989 Spain of Airfoil Textron Incorporated (ATI) patented a regular, 3-D braiding apparatus with a machine bed designed for the integration of braider and axial yarns. The machine surface consists of a grooved X-Y grid equipped with axial guides for the yarn supply lying beneath the grid on creels [23]. Inside the grooves sit the carriers whose movement is controlled by means of solenoids or fluid cylinders at opposing ends for each column and row (Figure 8) [23].

This patented design is noteworthy due to its inclusion of an innovative technique of fugitive (non-permanent) braider or carrier yarn removal following braiding. This procedure facilitates matrix impregnation, spacing control between non-fugitive (permanent) braider yarns and engineering of preform physical and mechanical properties [23]. In another embodiment of the machine bed for this design both axials and braiders are permanent, creating a resultant structure with improved mechanical properties [23]. Therefore, the Spain apparatus varies machine configurations in order to diversify the design potential for the resultant braided products.

In 1990 Ivsan and his associates of ATI patented a braiding apparatus having a cylindrical surface unlike flat, planar machine beds. This cylindrical or quadratic carrier surface serves to minimize the distance between carriers and the convergence point of the

forming braid (Figure 9) [15]. At opposite ends of the quadratic surface lie actuators of hydraulic or pneumatic form, which propel the carriers along support members or curved tracks comprising the bed [15]. The support members move sequentially as carriers transit adjacent tracks. A series of tubes on the tracks guide 'axial stuffer fiber strands' in a radial fashion [15].

The basic structure of the machine bed also includes stationary, independent base members that house spindles and guide rods [15]. In contrast to carrier movement the cylindrical bed does not allow independent axial movement relative to the support members [15]. The axial direction of motion forms a circular arc with respect to corresponding support members. The shifting of carrier paths across adjacent support members causes the intertwining of carrier and axial yarns to maintain proper yarn tensioning and convergence of the braid.

Fabrication of a multi-layer interlocked braided preform requires a machine bed which unlike track and column machines does not limit the insertion of 0° orientation yarns. This process is faster, allowing complex carrier systems movement and reducing the mechanical efficiency necessary to automate the process [3]. During the multi-layer interlock braiding process, carrier movement is both smooth and continuous. David Brookstein of Albany International Research Corporation (AIRC) commented, "the primary structural characteristics of multi-layer interlock braids are the nature of interconnectivity of adjacent laminae" [2]. The resultant braid consists of yarn that traverses from an original braided layer to an adjacent layer and back to the original layer.

AIRC has manufactured a multi-layer interlocking tubular braiding machine, equipped with five layered machine configuration. Each layer has the capability of braiding 48 yarns. A network of counter rotating horn gears propels the carriers along diagonal paths moving the yarns layer to layer of the preform [2]. The machine provides for up to 48 axials per layer. Thus, 480 yarns may be simultaneously braided. Another system developed by the AIRC group was designed to manufacture braided preforms of varying shapes. Cross-sections in the form of C, I, J, L, X, and Z are possible to construct on the system. The proposed system consists of a group of 4 x 2 track and gear modules [2]. These modules have "extra-modular" interlock positions which can be assembled to produce a given shape. The braided product of this system differs from the product of either the 4-step or 2-step process due to the yarn configuration patterns [2]. For instance, the yarns in one exterior layer of the interlocked structure need not pass through the adjacent

layer. Also, in contrast to the 2-step process, no axial yarns are needed for structural integrity [2].

CARRIER DESIGN

All 3-D braiding machines need sufficient yarn supplies delivered from movable housings, called carriers, which follow predetermined paths forming viable braided structures. Since the notion of moving a large yarn supply is problematical, the manufacture of small, compact and efficient carrier assemblies is crucial. Small carrier assemblies transit machine beds quickly and precisely. Yet, on flat, planar machine beds, due to their change of distance at the convergence point of the braid, these assemblies must retract yarn to prevent yarn slackening [13]. Thus the mechanism of the carrier serves to maintain a properly tensioned yarn, to allow feeding or retraction of the yarns (if necessary), and to direct the movement of yarn paths during the braiding process.

In 1987, William Heine of ARC filed a patent on an apparatus equipped with a main fiber spool which sat atop the fiber carrier [14]. The yarn follows a path from the main supply around a guide and through an aperture positioned within a take-up spool. The rotational axis of the main spool is perpendicular to the rotational axis of the take-up spool. This take-up spool is equipped with a tensioning device in the form of a spring assembly [14]. The carrier can be equipped with wheels for ease of movement.

Fulfilling the need for a carrier assembly that is compact, reliable and easily constructed, the Heine carrier also employs an adequate tensioning mechanism that has horizontal orientation above the yarn supply. This mechanism consists of a ratchet within the take-up spool that releases a pretensioned spring giving rotational force for the desired fiber tension [14]. While the braiding progresses, the take-up spool rewinds slack in the yarn preventing sagging. Also, constructed of a suitable material like metal or plastic, the carrier is economical.

The major claims of the patent provided a basis for future research and invention in the area of carrier design (Figure 10) [14]:

- (1) an elongated housing with an open end
- (2) a cap member mounted on the open end of the housing which is removable and
- (3) a take-up spool rotatably held on the cap member with perpendicular rotation to the axis of rotation of the supply spool.

The design is suitable for use on a multi-ply braiding machine which uses a matrix array of carriers undergoing alternate track and column shifts.

At the 3-D braiding laboratory of North Carolina State University, College of Textiles, El-Shiekh and his associates devised a suitable carrier device for the 2-step braiding process [20]. For the 2-step process, which requires an expansive yarn supply, the group designed and built a prototype having a large rewinding length. The prototype meets the requirements for successful carrier design by having continuous yarn supply and adequate tension level [18].

The NCSU carrier assembly had several notable features. First it is driven by a mechanical motor which feeds yarn, rewinds yarn and tensions the yarn (Figure 11) [20]. The action of the compact carrier is economical, furnishing a continual yarn supply with predetermined tension. The carrier made of steel has a rewinding length of fifteen feet [18]. The reliability of the carrier action compounded by its simplicity enhances the marketability of this prototype.

In 1990 Brown of ARC patented a fiber spool apparatus having a rewinding capability of smaller proportions as compared to the NCSU carrier assembly. Equipped with a motor housing, which consists of a coiled spring, axle and supply spool, the compact device advances yarn to the braiding apparatus (Figure 12) [5]. The carrier also has a tensioning mechanism similar to the NCSU design operation to adjust and maintain suitable levels of strand tension during braiding.

A fully automated braider equipped with well-tensioned carriers for the 2-step process was suggested by Du and his associates at the University of Delaware. The braider and its carriers not only fulfill the process requirements of effective speed, but also are cost effective. The system comprises "motorized" carriers mounted on a reformable track [11]. The system regulates carrier position at the start of each cycle (2-Step) due to the varying distance moved by each carrier. Each carrier assembly has a "fixed parking station" [11]. The carriers move from these stations simultaneously traversing in two steps and stopping at their next respective station.

The motorized carriers have the following components: (1) a small DC motor with gear head, (2) driving traction, (3) a bobbin holder permitting yarn retraction by an electronic tensioning device, (4) power contact - brushes and (5) an off/on control microswitch [11]. Thus, the Du motorized carrier system utilizes electronic and

mechanical devices that insure the precise carrier movement needed for the 2-Step process.

Yokoyama and his colleagues at Kyoto Institute of Technology, Japan, devised a computer-controlled system for driving the motion of carriers on a 3-D braiding machine. The system facilitates the change of the carrier track configuration [24]. Also, the system creates and modifies the carrier track for certain braid specifications.

This robot driven system is a noteworthy advancement. A robot answers optical sensors that cause the system to follow a guide-tape track plan [24]. A computer program dictates the relationship between carrier motion and yarn path. All processing parameters for carrier motion are programmed through the computer. The automated (self-driven) simulation controls both the carrier speeds and track positions for the construction of particular braids [24]. Also the computer simulates the product being formed by the carrier movement while activating the self-driven system.

The aforementioned ATI cylindrical braiding apparatus advanced not only the design of the machine bed, but served to reduce the complexity of carrier design. Its inventors realized that it is "desirable to minimize the difference between distances from a carrier member to the consolidation point..." [15]. The carrier members consist of T-shaped, platform bases for ease of sliding. The platform of the base has a spindle with a yarn supply. This platform includes a guide tube that carries yarn from a supply spool. No tensioning and retraction mechanism is needed due to the side by side carrier arrangement on the cylindrical machine bed. Next, for the manufacture of an axially reinforced braid, Spain and Bailey also designed carriers including "free-wheeling pulley assemblies" [15]. These assemblies mounted on support rods include a yarn supply and connect to a bias movable pulley along the guide rod axis.

BEAT-UP MECHANISMS

A necessary element for the production of 3-D braided preforms is the convergence of the structure to prevent fiber entanglement and to produce a uniform structure. With cartesian or 4-step braided structures, the convergence of the structure is obtained by the use of a beat-up or combing action. In most cases this beat-up action is performed manually, using rods, or by hand. Manual beat-up is not only labor intensive, but is slow and manufactures inconsistent products. In an effort to improve the

quality of the preforms, researchers are automating the beat-up process.

One of the earliest beat-up mechanisms is found in Florentine's MAGNAWEAVE process. In MAGNAWEAVE braiding, a combing action follows the intertwining of the yarns, controlling the orientation and density of the material [12].

In 1990, Ashton and Patterson of ARC developed a beat-up mechanism for multi-ply braiders. Monofilaments are mounted on one side of the braider with a rigid connection at one end and a flexible connection (such as a spring) at the other (Figure 13) [1]. Pusher arms take the lines to a central point between the fibers. At this point, gripper arms come in and grip or engage the lines, pulling them through to the other side of the braider. The gripper arms travel down support posts, bringing the interlacings down to the point of convergence [1]. The motion of the pusher and gripper arms can be controlled by hydraulic piston and cylinder devices.

At NCSU, El-Shiekh and his graduate students have developed a robotic arm to replace the beat-up motion usually performed manually. Utilizing a computer, a controller, two stepping motors, and a series of guide rods, a mechanical arm is used to bring the interlacings of fibers to the convergence point of the structure [18]. The beat up arm, after entering the area between carrier columns, swings up toward the convergence point while the beat-up unit travels parallel to the braider bed. This beat-up action is repeated for a designated number of positions along the braider bed. By positioning the beat-up arm between the carriers and moving the arm up and across the braider bed simultaneously, the contact between the fibers and the beat-up arm is minimized, thus reducing fiber damage due to the beat-up process [18]. In addition, the mechanized beat-up action produces a repeatable, uniform structure.

BIBLIOGRAPHY

1. Ashton, Clint H. and Gerald A. Patterson, "Combing Apparatus for Braiding Machine," U. S. Patent 4,898,067, 1990.
2. Brookstein, David S., "A Comparison of Multilayer Interlocked Braided Composites with other 3-D Braided Composites," 36th International SAMPE Symposium, Vol. 36, Book 1, April 15-18, 1991, pp. 141-150.
3. Brookstein, David S., "Interlocked Fiber Architecture: Braided and Woven," 35th SAMPE International Symposium, Vol. 36, Book 1, April 2-5, 1990, pp. 746-756.
4. Brown, Richard T., "Braiding Apparatus," U. S. Patent 4,753,150, 1988.
5. Brown, Richard T., "Fiber Spool Apparatus," U. S. Patent 4,903,574, 1990.
6. Brown, Richard T., "Through-the-Thickness Braiding Technology," 30th National SAMPE Symposium, March 19-21, 1985, pp. 1509-1518.
7. Brown, Richard T. and Eric Ratliff, "Method of Sequenced Braider Motion for Multi-ply Braiding Apparatus," U. S. Patent 4,621,560
8. Brown, Richard T. and Mabel E. Harman, "Advanced Textile Braiding Techniques," Advances in High Performance Composite Technology Conference, Clemson University.
9. Christianson, Carla, "3-D Fabrics Enhance End Product Performance," Industrial Fabric Products Review, January 1984, pp. 50-52.
10. Culp, Carl H., Steven M. Hastings and Richard T. Brown, "Braiding Apparatus," U. S. Patent 4,934,240, 1990.

11. Du, Guang-Wu et al, "Analysis and Automation of Two-Step Braiding," NASA Conference Publication 3038, Fiber-Tex 1988, Greenville, SC, Sept. 13-15.
12. Florentine, Robert A., "Magnaweave Automation: Status of 3D Braiding Manufacturing Technology," NASA Fiber-Tex 1988, Sept. 13-15, 1988.
13. Hammad, Mohamed A., "Staple Fiber Spinning Technology-3D Braiding," PH. D. Thesis, Alexandria University, Egypt, June 1991.
14. Heine, William M., "Fiber Spool Apparatus," U. S. Patent 4,700,607, 1987.
15. Ivsan, Thomas J. et al, "Apparatus and Method for Braiding Fiber Strands," U. S. Patent 4,922,798, 1990.
16. Klein, Allen J., "Braids and Knits: Reinforcement in Multi-directions," Advanced Composites, Sept./Oct. 1987, pp. 36-48.
17. Ko, Frank, "Braiding," Composites: Engineered Materials Handbook, Vol. 1, ASM International, 1987, pp. 519-528.
18. Li, Wei, "On the Structural Mechanics of 3D Braided Preforms for Composites," PH. D. Thesis, NCSU, Raleigh, NC, March 1990.
19. Li, Wei and Aly El-Shiekh, "The Effect of Processes and Processing Parameters on 3D Braided Preforms for Composites," SAMPE Quarterly, pp. 22-28.
20. Li, Wei et al, "Automation and Design Limitations of 3D Braiding Process," NASA Fiber-Tex 1989, 3rd Conference on Advanced Engineering Fibers and Textile Structures for Composites, Greenville, SC, Oct. 30-Nov. 1, 1989, pp. 115-140.
21. Pastore, Christopher, "Processing Science Model for Three Dimensional Braiding," PH. D. Thesis, Drexel University, Philadelphia, PA, March 1988.

22. Popper, Peter, "Braiding," Encyclopedia of Composites, VCH Publishers, September 1988.
23. Spain, Raymond G. "Method of Making Composite Articles," U. S. Patent 4,885,973, 1989.
24. Yokoyama, A. et al, "A New Braiding Process--Robotised Braiding Mechanism," Materials and Processing--Move into the 90's, 10th International SAMPE European Chapter Conference, July 11-13, 1989.

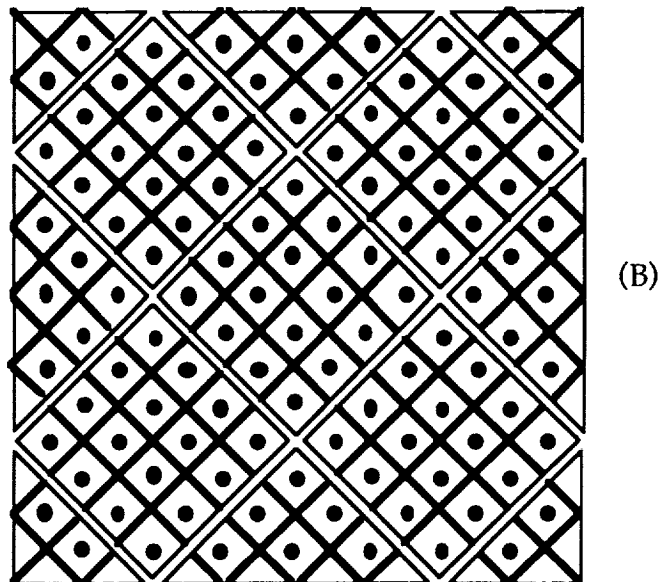
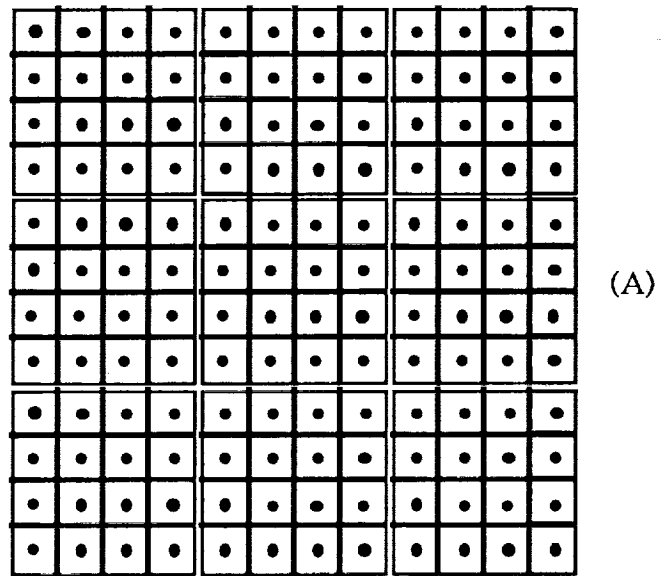


FIGURE 1: TWO ASSEMBLY ARRANGEMENTS FOR THE
2-STEP MACHINE BED

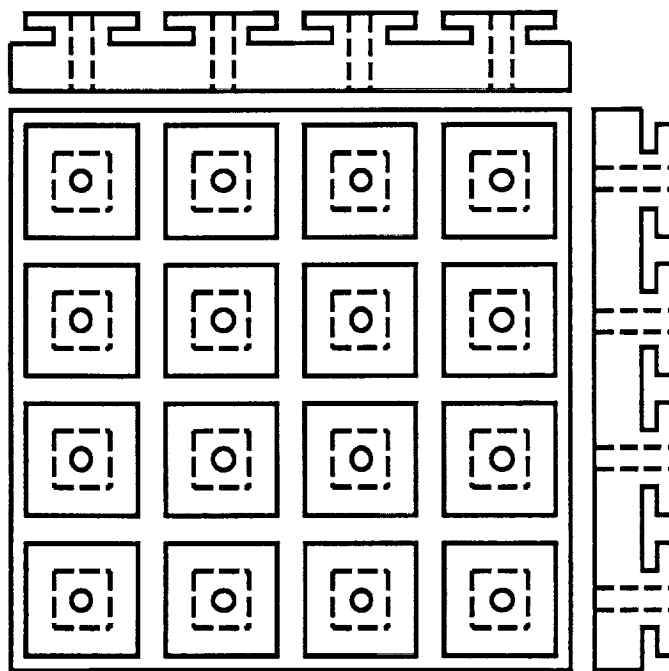


FIGURE 2: UNIT TILE OF THE 2-STEP MACHINE BED

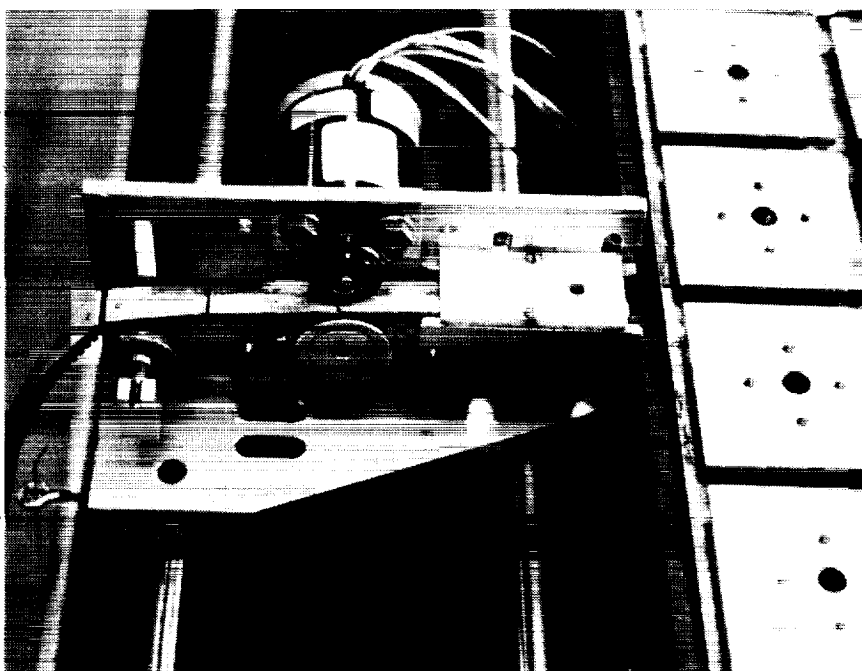


FIGURE 3: DRIVING UNIT OF THE 2-STEP MACHINE

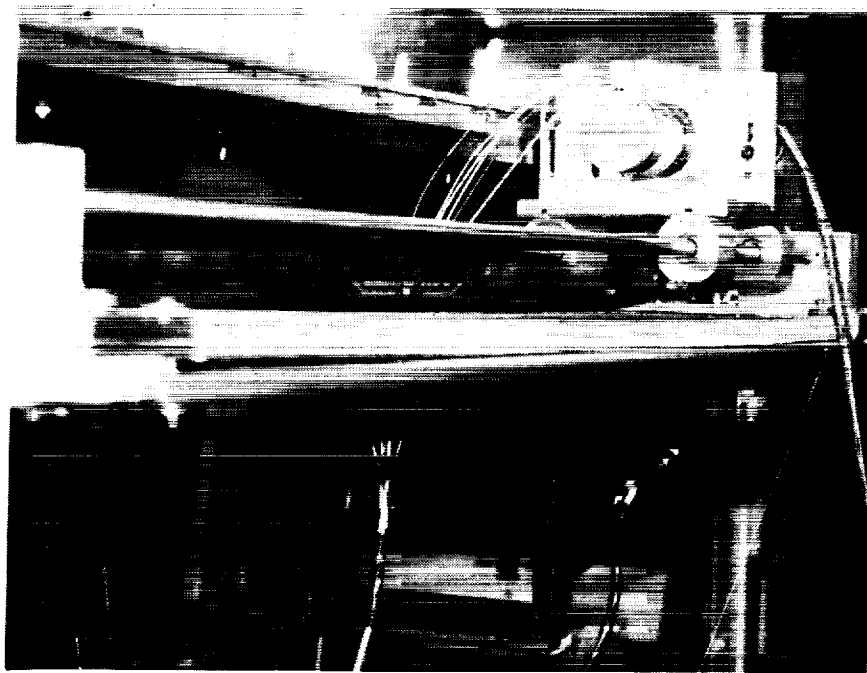


FIGURE 4: TRANSPORTATION SYSTEM FOR DRIVING
UNIT IN THE 2-STEP MACHINE

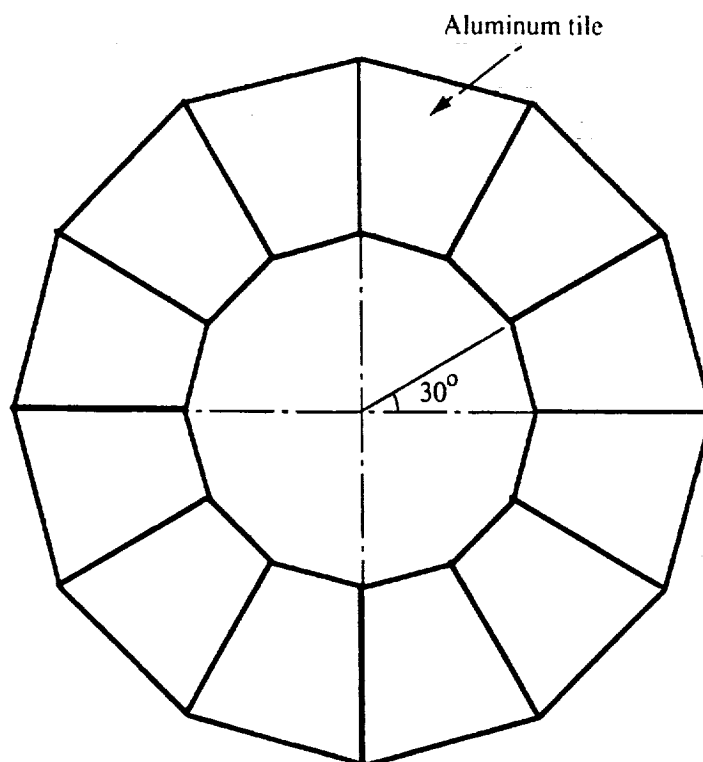
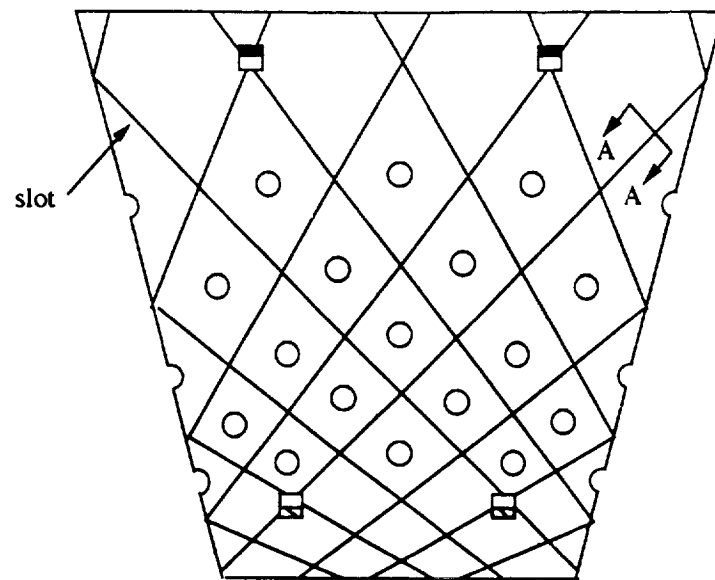


FIGURE 5: CIRCULAR CONFIGURATION OF 2-STEP
MACHINE BED



- | | |
|-------------------------|-----------|
| ○ axial yarn tube | ■ magnets |
| □ braiding yarn carrier | ▢ stopper |

FIGURE 6: A UNIT TILE OF THE 2-STEP CIRCULAR MACHINE BED

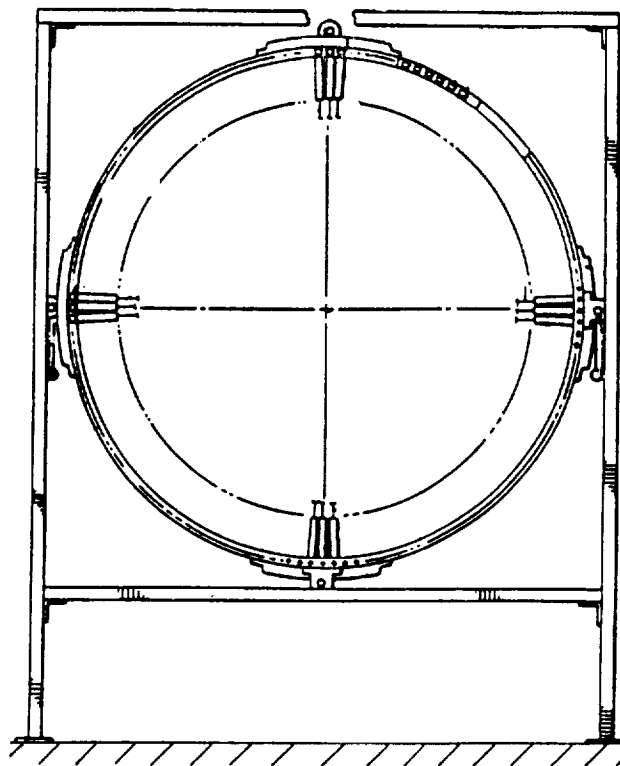


FIGURE 7: ARC CIRCULAR BRAIDING MACHINE

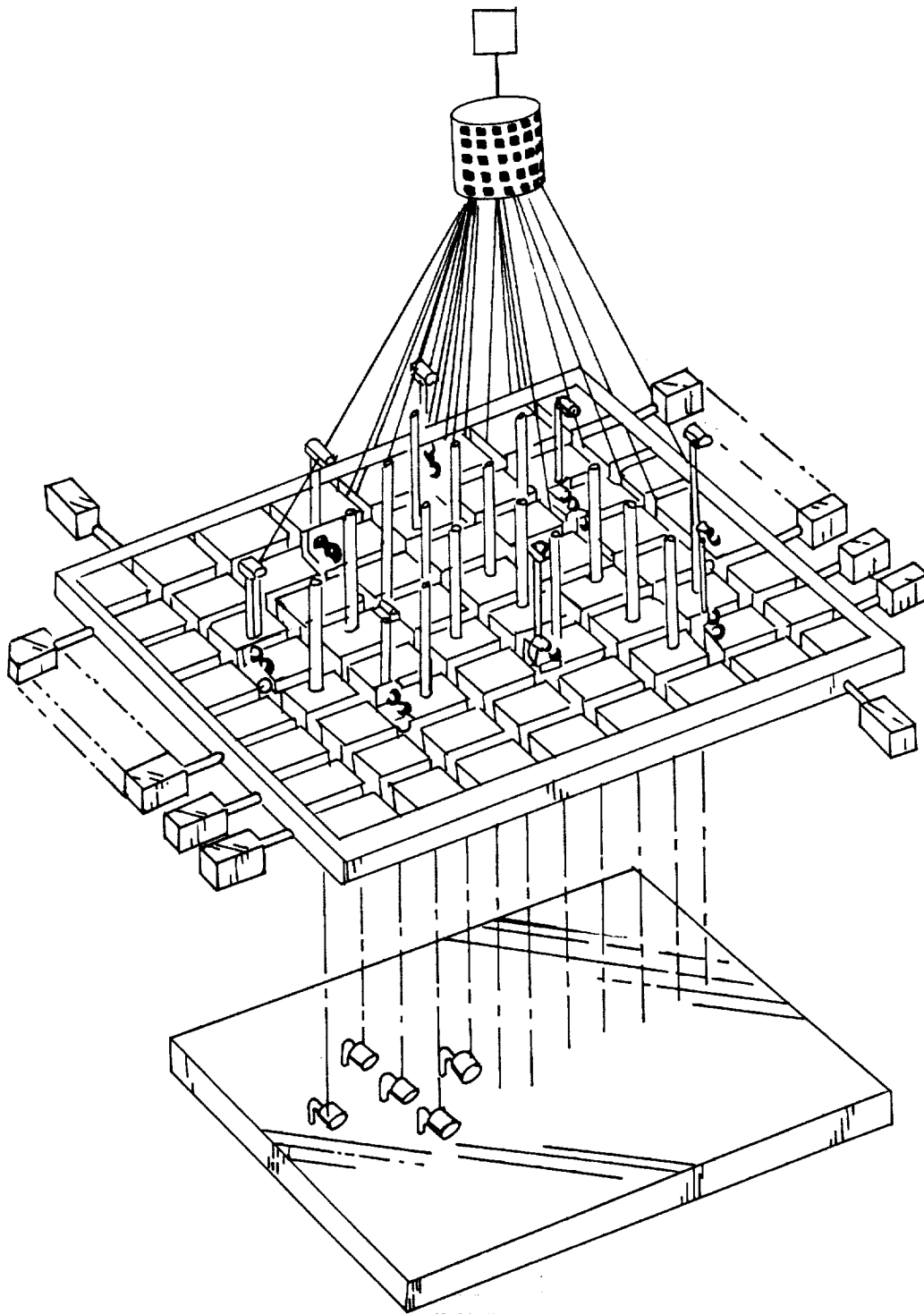


FIGURE 8: ATI 3-D BRAIDING APPARATUS

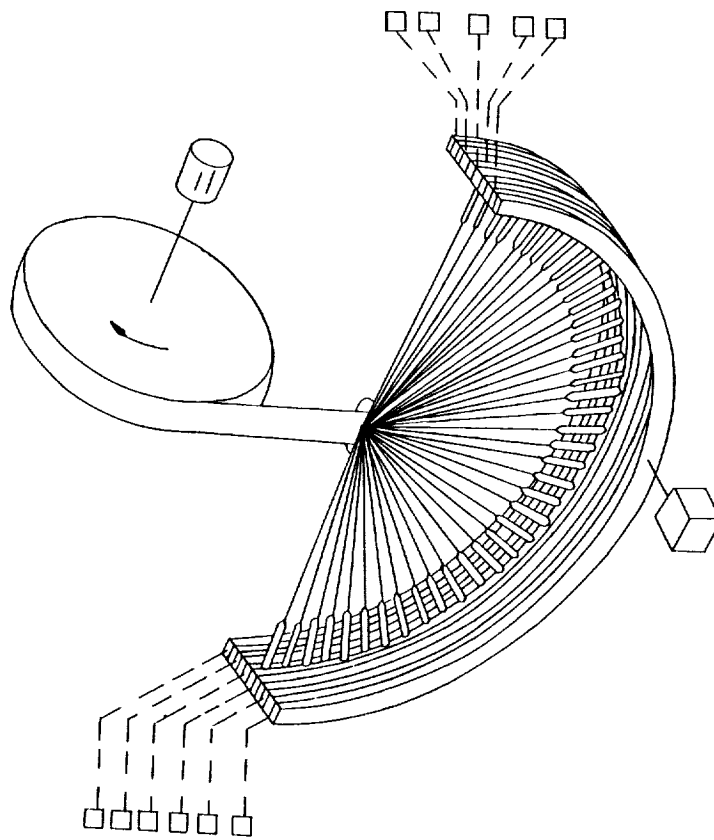


FIGURE 9: ATI CYLINDRICAL BRAIDING MACHINE

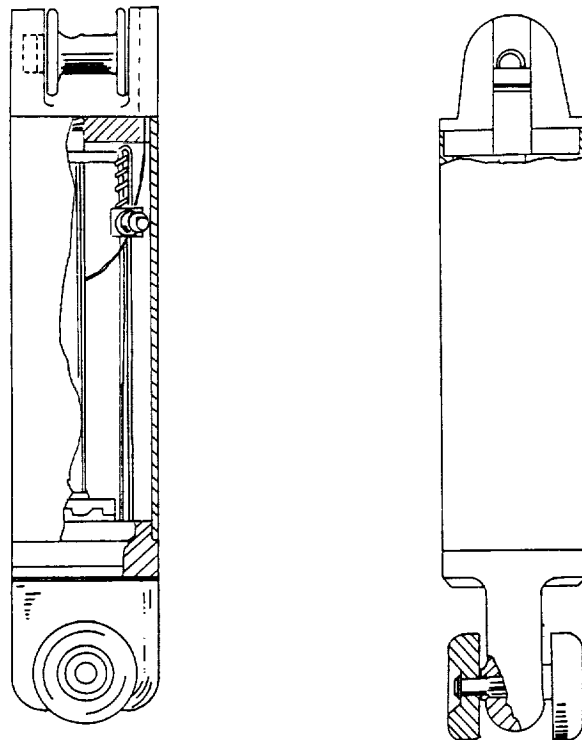


FIGURE 10: ARC CARRIER

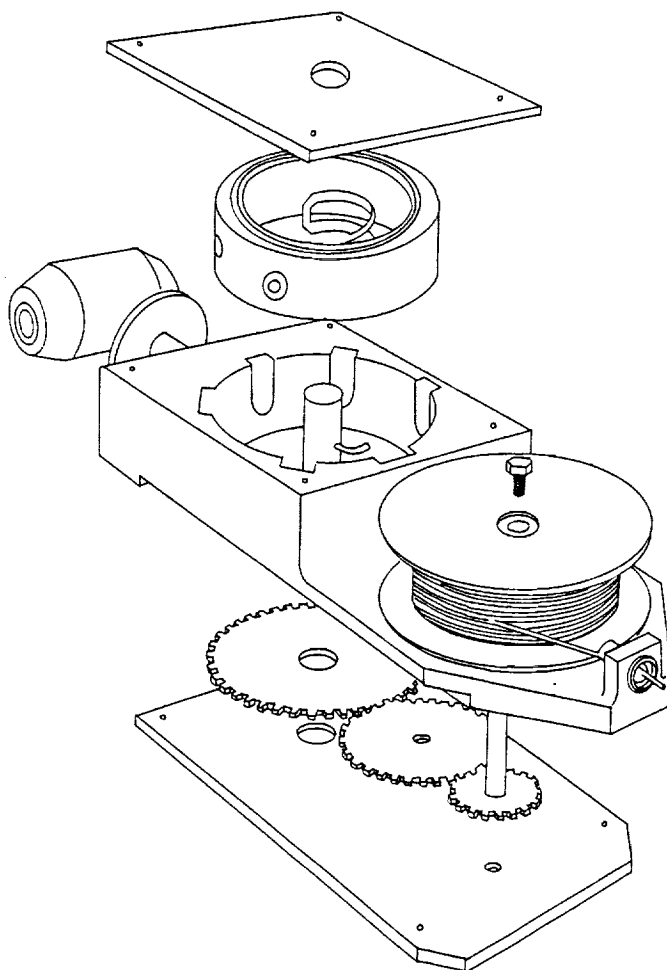


FIGURE 11: NCSU CARRIER ASSEMBLY

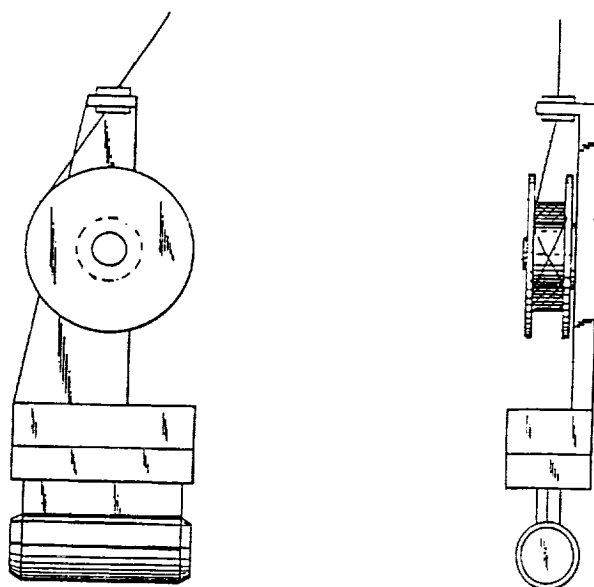


FIGURE 12: ARC CARRIER

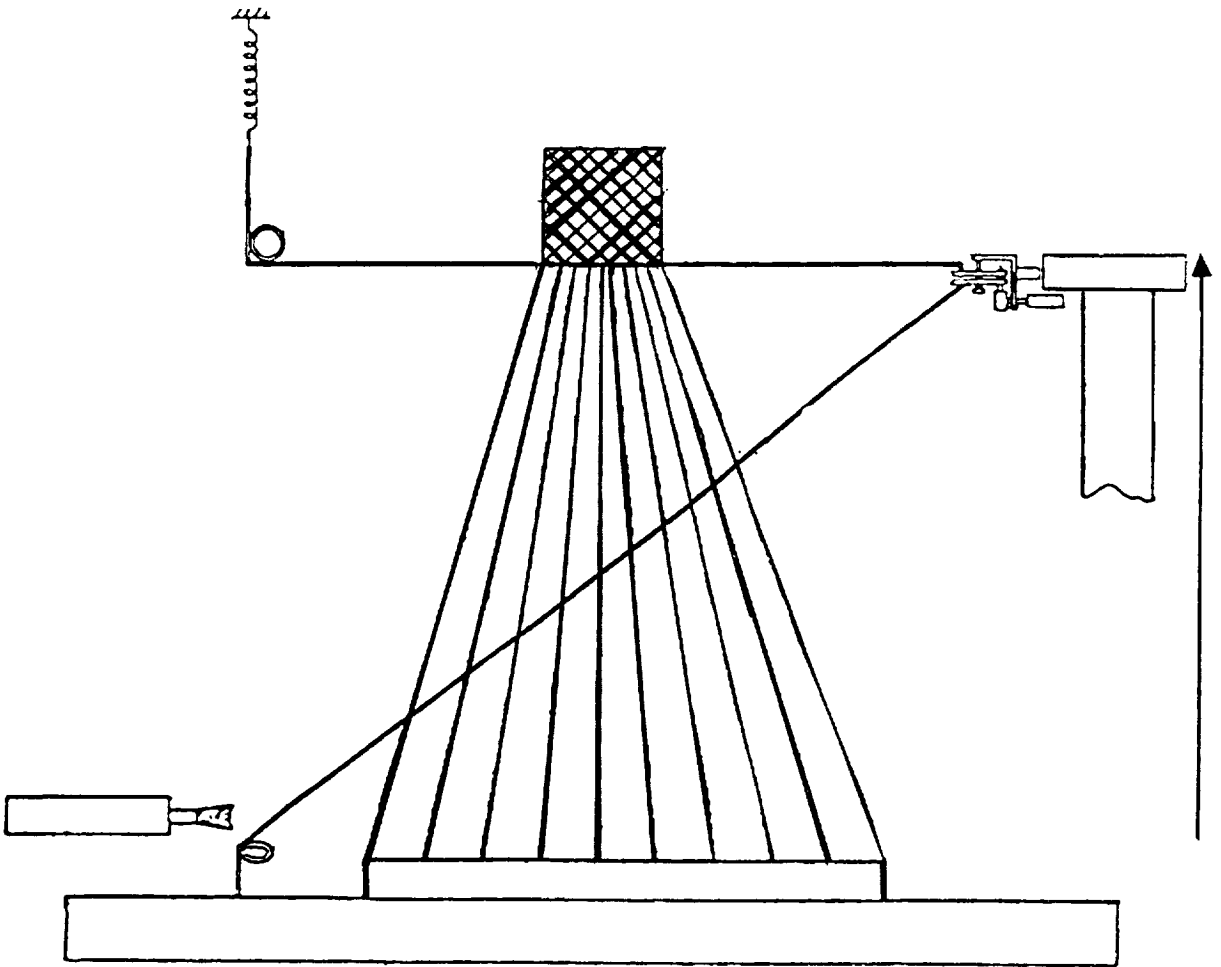


FIGURE 13: ARC BEAT-UP MECHANISM
FOR A MULTI-PLY BRAIDER

